Ocean Reference Stations

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1. PROJECT SUMMARY

The goal of this project is to maintain long-term surface moorings, known as Ocean Reference Stations, as part of the integrated ocean observing system. The scientific rational for these Ocean Reference Stations is to collect long time series of accurate observations of surface meteorology, air-sea fluxes, and upper ocean variability in regions of key interest to climate studies and to use those data to quantify air-sea exchanges of heat, freshwater, and momentum, to describe upper ocean variability and describe the local response to atmospheric forcing, to motivate and guide improvement to atmospheric, oceanic, and coupled models, to calibrate and guide improvement to remote sensing products and capabilities, and to provide anchor point for the development of new, basin scale fields of the air-sea fluxes. Model, satellite, and climatological fields of surface meteorology and air-sea fluxes have large errors; high quality, in-situ time series are the essential data needed to improve our understanding of atmosphere-ocean coupling and to build more accurate global fields of air-sea fluxes. Prediction and analysis of climate variability based on model or other products that have large errors in their atmosphere-ocean exchanges of heat, freshwater, and momentum is flawed; this effort to collect the critical in-situ flux time series and related efforts to develop air-sea flux products that use these Ocean Reference Stations as anchor points aim to remedy these flaws and greatly improve our understanding of how the atmosphere and ocean are coupled and together influence climate.

This project is now maintaining three Ocean Reference Stations at key locations: a site at 20°S, 85°W under the stratus cloud deck off northern Chile (Stratus), the Northwest Tropical Atlantic Station (NTAS) at 15°N, 51°W, and a site north of Hawaii near the Hawaii Ocean Timeseries (HOT) site. The surface buoys are equipped with Air-Sea Interaction Meteorology (ASIMET) systems developed at WHOI and capable of climate-quality measurements once per minute for one year. Telemetered near-real time data are provided to numerical weather prediction centers (but not included in their model runs, thus providing an independent means to examine model performance); these data are used to investigate model errors and biases and test improvements to the models. Data are also provided to validate remote sensing products and to guide development of new flux products. In addition, these data support research done by NOAA and other climate studies and these Ocean Reference Stations are coordinated with other flux reference sites. The Stratus Ocean Reference Station has proved to be a provider of key benchmark time series for examining atmospheric, coupled, and oceanic model performance in the important but challenging marine stratus region of the eastern tropical Pacific. The NTAS site is being upgraded as the prototype of implementation of real time telemetry of upper ocean data and coincident reporting of both surface flux and upper ocean heat content variability and anomalies.

2. ACCOMPLISHMENTS

The project is managed as four Tasks, with accomplishments reported by task.

Task I: Engineering, oversight and data

All three sites are now occupied by the modular-hull buoy (Figure 1). Hourly meteorological data are transmitted in near-real time via Argos telemetry and made available on an FTP server and a website with download capability. Data processing continues on schedule. The "best" quality meteorological and flux data is being made accessible through the web, typically within a year of recovery. New engineering and capability upgrades are being implemented and evaluated now at Stratus and at NTAS. In October 2007 and again in October 2008 an NDBC surface wave sensing and telemetry (Iridium) system was deployed on the Stratus buoy. In early 2007, the NTAS mooring was deployed with new hardware to permit telemetry of upper ocean data from instruments on the mooring line; this mooring was recovered and redeployed in the summer of 2008 with additional effort spent on the delivery of subsurface data in real time.

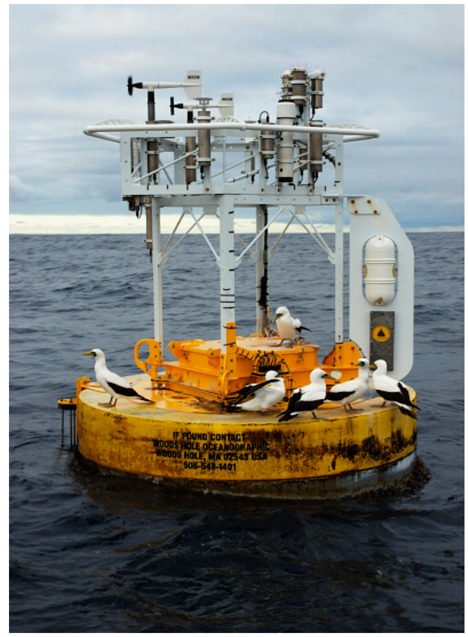

Figure 1. The new modular buoy in use at all Ocean Reference Stations. Photo taken during the 2006 Stratus deployment and recovery cruise.

Task II: Stratus Site

The stratus surface mooring was originally deployed in October 2000. It has been annually redeployed and recovered since that time, including the most recent done during the October 6 - November 3, 2008 cruise of the NOAA Ship *Ronald H. Brown*. This cruise was Leg 1 of two legs on the *Brown* as part of VOCALS (VAMOS Ocean Cloud Atmosphere Land Study); and the Stratus ORS provided one of the observational foci of this project. Accurate prediction of cloud amount and cover in marine stratus regions has long been a challenge; this is true off Peru and northern Chile. Further, model studies point to the dependence of the coupled climate variability of the Pacific Basin and surrounding continents to the atmosphere-ocean coupling in the stratus region. Thus, establishment and maintenance of an Ocean Reference Station in this critical but data sparse area has been a high priority. The Stratus ORS data has contributed significantly to the development and conduct of VOCALS.

Data recovery this year was good (though the RDI ADCP flooded), post-calibrations are being done, and equipment is still on the *Brown*. Post-calibrations and final data quality control will be done once the instruments return to WHOI in January 2009. On the buoy we measure air temperature, sea surface temperature, relative humidity, incoming shortwave and longwave radiation, wind speed and direction, rain rate, and barometric pressure. On the mooring line the instrumentation is concentrated in the upper 300m and measures temperature, salinity, and velocity. Hourly surface meteorological data are archived at WHOI (http://uop.whoi.edu/projects/Stratus/stratus.htm), arriving within hours of when it was observed. These data are exchanged in near real time with ECMWF and NCEP; they in turn provide operational data at the model grid point nearest the buoy. It is also shared with the Chilean Navy (SHOA). The same data are shared with CLIVAR investigators, especially modelers interested in the Stratus region and VAMOS/VOCALS investigators in the U.S. and in South America. This meteorological data are used to assess the realism of operational atmospheric models in the stratus region. Once per minute as well as hourly surface meteorological time series are provided to the VOCALS and other investigator communities (including Sandra Yuter, Chris Bretherton, Meghan Cronin) after recovery. The surface meteorological data have been made available to the satellite community (including radiation – Langley, winds – Remote Sensing Systems and JPL, SST – Dick Reynolds, all variables – the SEAFLUX project).

The oceanographic data are being used by Weller at WHOI to investigate air-sea coupling and upper ocean variability under the stratus deck. The initial archive is maintained by the Upper Ocean Processes Group at WHOI, which runs a public access server for their mooring data. The data are also available from OceanSITES (http://www.oceansites.org). We are collaborating with the Baseline Surface Radiation Network (BSRN) and the GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel. Long time series of incoming radiation along with the other coincident surface meteorological observations are very rare in the open ocean. The accuracy of the ORS radiation data has made them of high value for development of improved estimates of surface radiation fields over the oceans.

The Stratus ORS has been occupied since October 2000. We are now able (see Table 1, for example) to show how far climatological means of the air-sea fluxes, such as those computed from the 40-year ECMWF reanalysis (ERA-40), are incorrect in their representation of the atmosphere-ocean coupling under the very important stratus deck region off northern Chile. The ocean there receives more heat than ERA-40 suggests but the sky is cloudier (lower mean shortwave) than ERA-40 suggests. The additional gain comes from the observed latent, sensible, and longwave heat fluxes being smaller than indicated by the ERA-40 climatology. As an example of our collaboration with modeling centers, ECMWF retrieves our buoy data and does offline runs of modifications of the their atmospheric model to explore how to improve the realism of their model under the stratus clouds.

Table 1. Year-long means of the latent, sensible, longwave, shortwave, and net heat fluxes (net is the sum of the first four, where a positive sign indicates the ocean is being heated) from the first 5 deployments of the Stratus ORS compared to the 40-year mean ECMWF reanalysis values of these heat fluxes.

Variable	Stratus 1	Stratus 2	Stratus 3	Stratus 4	Stratus 5	ECMWF
Latent	-103.1	-118.0	-107.3	-99.0	-99.5	-124.6
Sensible	-7.0	-10.3	-7.1	-7.1	-5.0	-15.2
Longwave	-40.6	-49.2	-36.6	-21.7	-44.6	-55.0
Shortwave	202.0	199.5	190.4	191.3	183.5	220.2
Net	51.4	22.1	39.4	63.4	34.3	25.5

That models need to be improved is evident in Figure 2, a comparison of the daily-averaged incoming shortwave radiation climatology (average of six years of data) with the incoming shortwave radiation climatology from ERA-40 (ECMWF 40-year reanalysis) and NCEP-2 (National Center for Environmental Prediction reanalysis). During October to December, the models produce too few clouds, and as a consequence supply too much insolation to the sea surface, with the error close to 50 W m^{-2}.

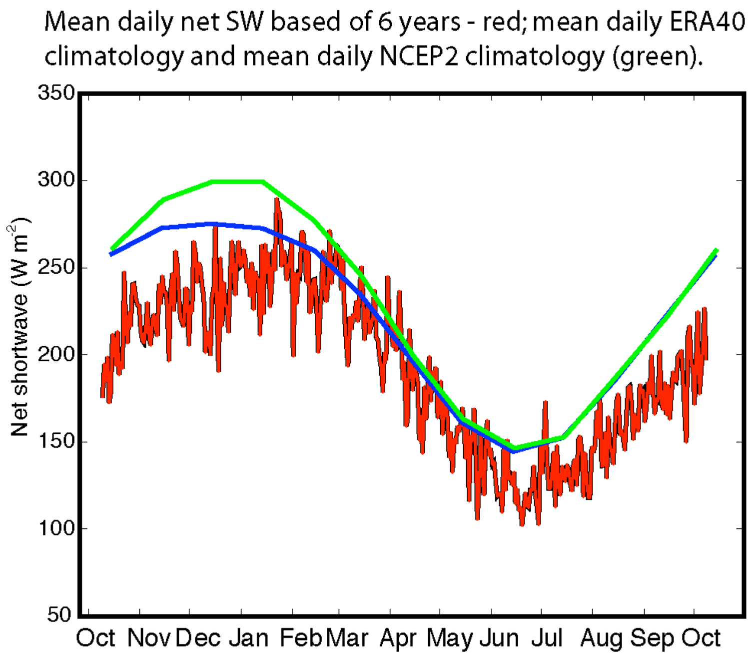

Figure 2. Comparison of observed incoming shortwave radiation at the Stratus Ocean Reference Station (mean daily, averaged over 6 years, in red) with the monthly climatological incoming shortwave radiation from ERA40 (blue) and NCEP2 (green).

The Stratus cruises serve the wider scientific community by providing a platform on which to study the regional ocean. Additional researchers who participated in collaborative research or benefited from shared ship time in FY2008 have come from many institutions: NOAA Earth System Research Laboratory, Servicio Hydrografico y Oceanografico de la Armada (SHOA, Chile), the NOAA National Data Buoy Center, Bigelow Laboratory, the Argo float program, the NOAA surface drifter program, and IMARPE (Institute of Marine Research, Peru). Ten Argo floats and 20 surface drifters were deployed during this year.

The work this year included recovering and redeploying the Chilean Navy tsunami warning buoy at 20°S, 75°W; this tsunami warning buoy was installed in 2006 with WHOI meteorological sensors on the surface buoy and ocean sensors on the mooring line. The deployment marked the beginning of a growing partnership between the ORS project and SHOA. We mount self-recording ASIMET modules on the tsunami buoy and temperature and temperature/salinity recorders on the buoy's mooring line (Figure 3.).

Figure 3. Chilean Navy (SHOA) DART buoy equipped with WHOI meteorological sensors. Shown here the internally recording sensor modules being recovered and replaced with fresh modules in October 2007.

Task III: NTAS Site

The Northwest Tropical Atlantic Station (NTAS) project for air-sea flux measurement was conceived in order to investigate surface forcing and oceanographic response in a region of the tropical Atlantic with strong SST anomalies and the likelihood of significant local air-sea interaction on seasonal to decadal time scales. The strategy is to maintain a meteorological measurement station at approximately 15^{o} N, 51^{o} W through successive (annual) turn-arounds of a surface mooring. Redundant meteorological systems measure the variables necessary to compute air-sea fluxes of heat, moisture and momentum using bulk aerodynamic formulas.

NTAS has two primary science objectives: 1) Determine the air-sea fluxes of heat, moisture and momentum in the northwest tropical Atlantic using high-quality, in-situ meteorological measurements from a moored buoy. 2) Compare the in-situ fluxes to those available from operational models and satellites, identify the flux components with the largest discrepancies, and investigate the reasons for the discrepancies. An ancillary objective is to compute the local (one-dimensional) oceanic budgets of heat and momentum and determine the degree to which these budgets are locally balanced.

A mooring turn-around cruise was planned on the NOAA ship *Ronald H. Brown* in during May 2008 order to retrieve the existing mooring (NTAS-7) and replace it with a new mooring (NTAS-8). Unforeseen circumstances resulted in the *Brown* being the shipyard for maintenance during the planned cruise period. As a result, the turn-around cruise was re-scheduled on the *RV Oceanus* for the period 14 July to 1 August 2008, about 8 weeks later than planned. In preparation for this cruise, three ASIMET systems were calibrated and tested, and two systems, comprised of the best performing sensors, were prepared for deployment. The NTAS-8 mooring was deployed on 28 July 2008 and the NTAS-7 mooring was recovered on 29 July. The period between deployment and recovery was dedicated to a comparison of the two buoy systems, with the shipboard system as an independent benchmark. Data return from NTAS-7 was very good during the first 14 months, with all meteorological sensors showing complete records except for SST, for which one system had 72% return. Since the second system had a complete record, no data will be missing in the first 14 months of the final (combined) data set. However, because the service cruise was delayed, the ASIMET logging system, designed for a maximum of 14 months of operation, terminated data acquisition prior to servicing. This will result in a data gap of about 20 days between NTAS-7 and NTAS-8

NTAS surface meteorological data are archived on the UOP web site (http://uop.whoi.edu/projects/NTAS/ntas.htm) and also available in near real time from the NDBC web server (http://www.ndbc.noaa.gov). Data are exchanged with ECMWF and NCEP, and they in turn provide operational model output at the grid point nearest the buoy. NTAS data are also available through OceanSITES (http://www.oceansites.org) and are shared with the Baseline Surface Radiation Network (BSRN) and the GEWEX (Global Energy and Water Cycle Experiment) Radiation Panel.

The 2008 NTAS cruise represented the second year of collaboration with the Meridional Overturning Variability Experiment (MOVE). The MOVE effort involved mooring turnarounds and data offload from several Pressure/Inverted Echo Sounders (PIES; Figure 4). Subsurface moorings were recovered and re-deployed at the MOVE site (about 40 nmi northwest of the NTAS site) as well as the M3 and M4 sites (along the continental slope near Guadeloupe). Acoustic telemetry was used to offload data from PIES located at MOVE sites M1-M4 and M7.

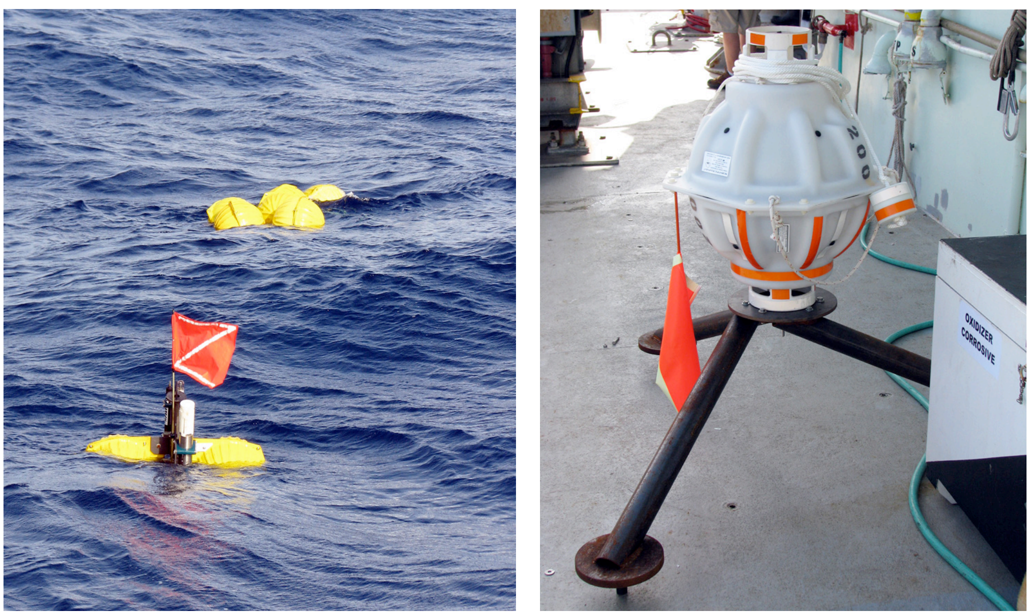

Figure 4. Flotation from MOVE subsurface mooring at the surface prior to recovery (left). Pressure/Inverted Echo Sounder (PIES) sensor ready for deployment (right).

The NTAS-8 mooring represented the second year of development for real-time telemetry of subsurface data. Engineering work undertaken as part of the WHOI VOS project resulted in an acoustic telemetry subsystem utilizing two Benthos underwater acoustic modems (Figure 5) interfaced to an Iridium communication controller through the same electromechanical interface developed for NTAS-7 (Figure 6). Using these new electronics, the mooring was outfitted with a prototype system for both inductive and acoustic telemetry of underwater instruments. Unfortunately, despite successful testing of all system components prior to assembly, the fully assembled system did not function as expected at sea prior to deployment. Several rounds of debugging were executed at sea, but ultimately the NTAS-8 mooring was deployed without a functional subsurface telemetry system. A similar system has since been assembled and successfully tested for another project, and we expect the NTAS-9 system to be fully functional.

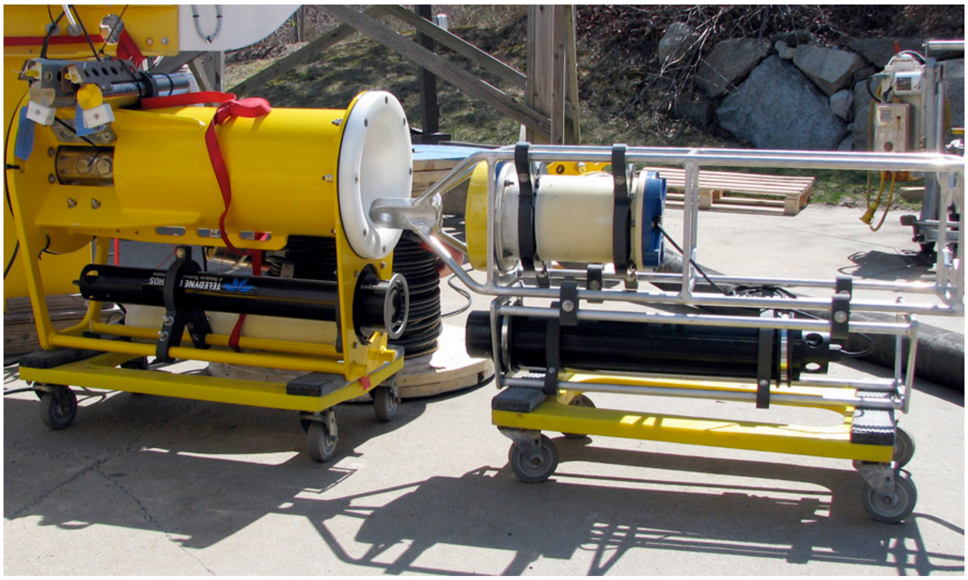

Figure 5. Pre-deployment testing of NTAS-8 acoustic telemetry subsystem, with upper acoustic modem mounted at bell mouth flange (left) and lower acoustic modem attached to ADCP cage (right).

Figure 6. NTAS-7 telemetry hardware prior to deployment. Fully assembled telemetry interface section laid out on deck and connected to the buoy, showing bell-mouth flange and wire-coupling assembly (foreground), compliant electro-mechanical section, and universal joint and upper flanged spacer at the buoy hull.

For the telemetry trial on NTAS-8, the mooring line was outfitted with four instruments from the UOP inventory which contained inductive modems: Three Seabird SBE-37s at 25, 45 and 65 m and a Sontek Argonaut current meter 14 m.

Task IV: Hawaii Site

The Hawaii Ocean Time-series (HOT) site, 100 km north of Oahu, Hawaii, has been occupied since 1988 as a part of the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). Among the HOT science goals are to document and understand seasonal and interannual variability of water masses, relate water mass variations to gyre fluctuations, and develop a climatology of high-frequency physical variability in the context of interdisciplinary time series studies. The primary intent of the WHOI Hawaii Ocean Timeseries Station (WHOTS) mooring is to provide long-term, high-quality air-sea fluxes as a coordinated part of the HOT program and contribute to the goals of observing heat, fresh water and chemical fluxes at a site representative of the oligotrophic North Pacific Ocean. It is expected that establishment of the WHOTS mooring will accelerate progress toward understanding multidisciplinary science at the site, provide an anchor site for developing air-sea flux fields in the Pacific, and provide a new regime in which to examine atmospheric, oceanic, and coupled model performance as well as the performance of remote sensing methods.

The observational strategy is to maintain a surface mooring at approximately

22.75° N, 158° W, instrumented to obtain meteorological and upper ocean measurements, through successive (annual) turnarounds done in cooperation with HOT investigators. Redundant meteorological systems on the surface buoy measure the variables necessary to compute air-sea fluxes of heat, moisture and momentum using bulk aerodynamic formulas. Subsurface oceanographic sensors on the mooring are being provided through cooperation with Roger Lukas (U. Hawaii; funded by the National Science Foundation).

A mooring turn-around cruise was conducted on June 3-11, 2008 on the U. Hawaii ship *Kilo Moana*. The field work was done in cooperation with Roger Lukas and other HOT investigators from U. Hawaii. In preparation for this cruise, three ASIMET systems were assembled and tested. The WHOTS-5 mooring was deployed and the WHOTS-4 mooring was recovered. The period between deployment and recovery was dedicated to a comparison of the two buoy systems, with the shipboard system as an independent benchmark. The standard *Kilo Moana* meteorological sensors were complemented by installation of a UOP AutoIMET system similar to that used on Volunteer Observing Ships. Data return from the two WHOTS-4 ASIMET systems was very good. The remaining sensors operated for the full 368 days deployment.

We invited Dr. Frank Bradley of CSIRO, Canberra, Australia to participate on the cruise. He assisted in intercomparison of the shipboard and moored meteorological systems. We also continued ongoing analyses of the performance of shortwave and longwave radiometers at sea.

Commercial bird barrier strips were installed on the WHOTS-3 buoy to reduce data contamination and sensor shadowing due to birds and their accompanying guano deposition. Evaluation of the buoy prior to and after recovery indicated that the prevention efforts were largely successful, little evidence of birds having perched on the on the tower and sensors. The same barrier strips were installed on the WHOTS-4 buoy. Installation on the WHOTS-5 buoy found that the spot welds on these strips are slightly magnetic, so care is required in not placing these too close to the compass of the anemometer.

In cooperation with C. Sabine of PMEL, and with the assistance of D. Sadler (U. Hawaii), a pCO2 system was incorporated in the WHOTS-5 buoy (Figure 7) as it had been in the WHOTS-4 buoy. Incorporation of CO2 measurements on the WHOTS buoy provided continuation of the time series begun in 2004 from the MOSEAN buoy. CO2 measurements are made every three hours in ambient air and in air equilibrated with surface seawater using an infra-red detector. A summary file of the measurements is transmitted once per day and plots of the data are posted in near real-time to the web. To view the daily data visit the NOAA PMEL Moored CO2 Website: http://www.pmel.noaa.gov/co2/moorings/hot /hot_main.htm. Within a year of system recovery, the final processed data are submitted to the Carbon Dioxide Information Analysis Center (CDIAC).

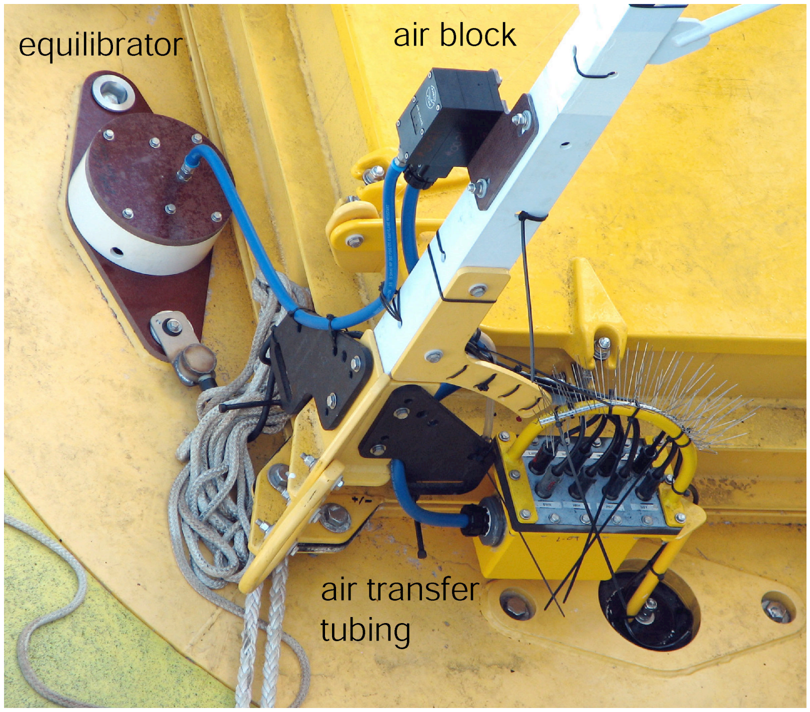

Figure 7. Principal external components of pCO2 system on the WHOTS-4 buoy. The equilibrator tube extends through a hole in the foam hull into the water below. Air transfer tubing within a protective conduit (blue) connects the equilibrator to the air block and the air block to instrumentation inside the buoy well.

3. PUBLICATIONS AND REPORTS

Bouchard, P., J. Lord, N. Galbraith, G. Allsup, S. Whelan, A. Plueddemann and R. Weller, 2008. "Inductive telemetry for UOP Ocean Reference Station Moorings", ONR/MTS Buoy Workshop, 4-6 March 2008, Bay St. Louis, MS.

Colbo, K. and R. A. Weller, 2008: The accuracy of the IMET sensor package in the subtropics. *J. Atmos. Oceanic Technol.*, in review.

Ghate, Virendra P., Bruce A. Albrecht, Christopher W. Fairall, and Robert A. Weller, 2008: Climatology of Surface Meteorology, Surface Fluxes, Cloud Fraction and Radiative Forcing over South-East Pacific from Buoy Observations, *J. Cimate,* submitted.

Plueddemann, A., F. Bahr, L. Yu and R. Weller, 2008. "Observed and Modeled Longwave Radiation in the North Pacific During 2004", NOAA Office of Climate Observation Annual System Review, Silver Spring, MD, 3-5 Sept 2008.

Upper Ocean Processes Group, 2007. “The Oceanscience underway CTD”, UOP Tech Note, August 2007, contributed by S. Whelan and Jochen Klinke. http://uop.whoi.edu/techdocs/technotes.html

Upper Ocean Processes Group, 2007. “Inductive telemetry for UOP Ocean Reference Station Moorings”, UOP Tech Note, December 2007, contributed by A. Plueddemann, J. Lord, G. Allsup and N. Galbraith. http://uop.whoi.edu/techdocs/technotes.html

Vialard, J., J. P. Duvel, M. J. McPhaden, P. Bouret-Aubertot, B. Ward, E. Keys, D. Bourass, R. Weller, P. Minnett, A. Weils, C. Cassous, L. Yard, T. Fristedt, F. Marsac, C. Menkes, S, Kennan, 2008. CIRENE: Air-sea interactions in the Seychelles-Chagos thermocline ridge region. *Bull. Amer, Meteor. Soc*., in press

Weller, R.A., 2007. “The Air-sea coupling under the persistent stratus deck in the Southeast Pacific”, European Geophysical Union, Vienna, Austria.

Weller, R.A., 2007. “The status and needs of long time series observations”, POGO-9 Meeting, Bermuda, January 2008.

Weller, R.A. and J. T. Farrar, 2008. “Buoy-based observations of the diurnal cycle in upper-ocean and surface meteorological properties”, Ocean Sciences Meeting, Orlando, FL.

Weller, R. A., Bradley, E. F., Edson, J., Fairall, C., Brooks, I., Yelland, M. J., and Pascal, R. W., 2008. Sensors for physical fluxes at the sea surface: energy, heat, water, salt, *Ocean Sci. Discuss*., 5, 327-373.

Whelan, Sean P., Al Plueddemann, Roger Lukas, Jeffrey Lord, Paul Lethaby, Jeffrey Snyder, Jason Smith, Frank Bahr, Nan Galbraith, and Chris Sabine, 2008: WHOI Hawaii Ocean Timeseries Station (WHOTS): WHOTS-4 2007 Mooring Turnaround Cruise Report. *Technical Report, WHOI-2008-4*, UOP 2008-02, 120 pages.

Whelan, Sean, Jeff Lord, Carmen Grados, Lisan Yu, Luis Morales, Nancy Galbraith, Simon P. deSzoke, Megan O’Leary, Robert Weller, Paul Bouchard, Tom Farrar, and Frank Bradley, 2008. Stratus Ocean Reference Station (20°S, 85°W). Mooring Recovery and Deployment Cruise. Stratus 8. R/V Ronald H. Brown Cruise 07-09. October 9, 2007 – November , 2008. *Technical Report, WHOI-2008-01, UOP 2008-01,* 110 pages.

Yu, L., R. A. Weller, 2008. Objectively Analyzed air-sea heat Fluxes (OAFlux) for the global ice-free oceans. Bull. Amer. Meteor. Soc., 88(4), 527-533.

Yu, L., X. Jin, and R. A. Weller, 2008. Air-sea turbulent heat flux estimates at the global buoy sites. *J. Geophys. Res*, submitted.